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AD NUMBER
ADC011774
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FROM: confidential
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NRL ltr, 4 Dec 1996; NRL ltr, 4 Dec 1996

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UNITED STATES GOVERNMENT

memorandum

7103/144

DATE: 4 December 1996

FROM: Burton G. Hurdle (Code 7103)

SUBJECT: REVIEW OF REF. (a) FOR DECLASSIFICATION

TO: Code 1221.1

VIA: Code 7100

REF: (a) NRL Confidential Report #1066 by Wilmer Lawson, 16 Mar 1960

1. Reference (a) discusses means of providing the optimum power amplifier design to accommodate the variation of transducer impedance in the ARTEMIS array. The ARTEMIS program was an experimental research program at low frequencies (400 Hz) to detect and track submarines. The program was not fully completed and never reached operational utilization.

2. The technology and equipment of reference (a) have long been superseded. The current value of this report is historical.

3. Based on the above, it is recommended that reference (a) be declassified and released with no restrictions.

Burton G. Hurdle

BURTON G. HURDLE
Acoustics Division

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MOST Project -4 CNTB

[redacted]

NRL Memorandum Report 1006

PROJECT ARTEMIS

Analysis of Transducer-Impedance Variations on the Amplifier Operation

Project ARTEMIS High-Power Acoustic Source

(Unclassified Title)

Wilmer Lawson

SOUND DIVISION

ADC011774

16 March 1960

U. S. NAVAL RESEARCH LABORATORY

Washington, D.C.

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Memorandum Report 1066

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PROJECT ARTEMIS.

Analysis of Transducer-Impedance Variations on the Amplifier Operation.

Project ARTEMIS High-Power Acoustic Source (U).

"EXCLUDED FROM GENERAL DECLASSIFICATION SCHEDULE" PRESCRIBED BY E. O. 11652

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By

12 39p.

10 Wilmer Lawson

14 NRL-MR-1066

"NATIONAL SECURITY INFORMATION"

"Unauthorized Disclosure Subject to Criminal Sanctions"

16 March 1960

Electrical Applications Branch
Sound Division
U. S. NAVAL RESEARCH LABORATORY
Washington, D. C.

5200517-60

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ABSTRACT

The impedance which a tuned sonar transducer presents to a power amplifier may vary widely by as much as two to one. Since most amplifiers are designed to provide as much output power as is permitted by the dissipation rating of the active devices, the variation, by increasing the dissipation when an impedance reduction occurs, requires a reduction in output power to allow for the increase in dissipation, and results in poor utilization of the active devices and in lower efficiency.

The expected variation in impedance of the 400 cps ARTEMIS transducer while large, is not too large to completely prohibit system operation if the maximum power output is held to 1.0 Mw per amplifier, 4.0 Mw total, particularly for the contemplated noise signals. The variation is sufficiently large to make desirable some form of compensation to reduce the amount without adversely affecting the system efficiency.

Such a system is a network which is parallel tuned at a frequency above the transducer center frequency and then series tuned at the point of maximum resistance of the transducer to prevent a reduction in system efficiency. The values of the network parameters are parallel coil inductance - 1.98 mh, coil resistance - 1.108 ohms, parallel capacitance - 66.2 uf., and series capacitance - 51.6 uf. With such a network, operation with any kind of signal over a band of greater than 100 cps is permissible.

To maintain high efficiency, and prevent excessive dissipation, the amplifiers should be operated only at full output or at 20% of full output. This will result in outputs of 4, 3, 2, 1, 0.5 and 0.2 megawatts which are approximately two to three db variations. It is also possible to operate the system with less than the full complement of ten transducer elements in the array.

PROBLEM AUTHORIZATION

ONR NR 287 002, AS 02101
NRL Problem Number 55S05-21

PROBLEM STATUS

This is an interim report on one phase of the project. Work is continuing.

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INTRODUCTION

Electro-mechanical transducers used in sonar applications present a variable impedance load to the amplifier. Both the magnitude and phase angle of the transducer impedance vary widely over the useful frequency range of operation. This variation can have quite serious effects on the amplifiers which supply the electrical power, causing large changes in output power, accompanied by either severe distortion, excessive dissipation, or both.

If, therefore, effective operation over wide frequency bands, either with noise or with single-frequency sinusoidal signals, is desired, an analysis of the load impedance and its effect on the power amplifier must be made. This report describes such an analysis for the amplifiers and transducers used in Project ARTEMIS. It also indicates methods whereby the impedance variation may be reduced, both in magnitude and in phase, and gives values of these network parameters for the specific components used with Project ARTEMIS. The effect of the line and matching transformer parameters upon this network is included, and the transformation ratio of the matching transformer is determined.

BACKGROUND

The operation of power amplifiers may be described in a general nature with the aid of the two types of output-characteristic curves, i. e., I versus E for different values of the input parameter, which are obtainable from the active devices used in the amplifier. These are the familiar triode and pentode or beam-tetrode characteristics published in tube manuals. With regard to the effects of load changes, transistor characteristics are equivalent to pentode-tube characteristics.

Idealized, the output characteristics of low and high-efficiency triodes are shown in Figure 1a and 1b, respectively, and those of pentodes and transistors are shown in Figure 1c. Approximate output and DC-input powers of a class-B amplifier, assuming sinusoidal output voltage and current and a DC level of the active device current of 0.333 I pk, are computed for a nominal, or matched, load impedance, and for a value of load of approximately one-half the nominal value. These values of power are given in Table I.

Generalizing, it may be stated that, for a constant input parameter, the dissipation in triodes is approximately inversely proportional to the load impedance, increasing proportionately as the maximum efficiency is increased. In pentodes, the dissipation is also approximately inversely proportional to the load impedance. The chief difference in the operation of the two types with constant drive is

[redacted]

the efficiency, which is lower but more nearly constant, with triodes. Pentode operating efficiency is inversely proportional to the load impedance.

Distortion in a triode is not severely affected by the load impedance, but, in pentodes, is increased manyfold with load impedances which are greater than the matched value. It should be noted that the input power requirement is nearly constant in pentode-type power amplifiers, and that they can be considered to be constant current generators.

If pentodes or transistors are operated with large amounts of feedback by using cathode-follower or common-collector operation, the dissipation, output power, and efficiency behave similarly to a high-efficiency triode, and clipping with increased load impedance is eliminated. Circuit gain becomes very small, however, and the filament-cathode voltage limitation forbids the use of vacuum tube cathode followers for power amplifiers. Such amplifiers can be considered to be constant voltage generators.

Even as the magnitude of the amplifier load impedance causes changes in the operating characteristics, so the phase angle of the load causes changes in the dissipation of the active devices in the amplifier. Assuming that the load impedance remains constant, the peak voltage and peak current output of the amplifier are constant. Since DC-input power is a function of a constant supply voltage and the peak current, this power will be a constant. The output power in the load, however, is a function not only of the peak voltage and peak current, but also of the phase angle of the load. The difference between the volt-ampere output (VI) and the real-power output (VICos θ) must be dissipated within the amplifier, in addition to the normal operating dissipation (P_{dc}-VI). It is for this reason that the sonar-transducer load usually must be tuned so that the amplifier sees as near unity-power-factor load as possible.

A general expression for the dissipation in the active devices of a class-B amplifier which will account for signal shape, device efficiency, and load phase when the peak voltage and peak current are known may be obtained from the equation

$$P_d = P_{in} - P_{out}. \qquad 1.$$

For any type of signal, noise or otherwise, the output power is

$$P_{out} = \frac{E_{pk} I_{pk} \cos \theta_L}{R_p^2}, \qquad 2.$$

where R_p is the peak-to-rms ratio of the signal and θ is the phase angle of the load impedance. The DC-input power in all cases is

$$P_{in} = \frac{E_{cc} I_{pk}}{R_p F}, \qquad 3.$$

where F is the form factor or ratio of the rms to the average value and E_{cc} is the DC-supply voltage.

If the output power is assumed constant, the peak current may be expressed, for $\cos \theta_L = 1$, as

$$I_{pk} = \frac{P_{out} R_p^{\,2}}{E_{pk}}. \qquad 4.$$

By substituting equation 4 in equation 3, and by using equation 3, equation 1 can be rewritten as

$$P_d = \frac{P_{out} E_{cc} R_p^{\,2}}{E_{pk} F R_T} - P_{out}. \qquad 5.$$

Factoring and collecting terms in equation 5 yields, for $\cos \theta_L =$ 1.0,

$$P_d = P_{out} \left(\frac{E_{cc} R_p}{E_{pk} F} - 1 \right). \qquad 6.$$

To account for non-unity power-factor loads, the output power must be changed to a volt-ampere output and the reactive volt-amperes must be added to equation 6. This gives

$$P_d = V.A. \left(\frac{E_{cc} R_p}{E_{pk} F} - 1 \right) + \left(V.A. - V.A. \cos \theta_L \right) \qquad 7.$$

and

$$P_d = \frac{E_{pk} I_{pk}}{R_p^{\,2}} \left(\frac{E_{cc} R_p}{E_{pk} F} - 1 \right) + \frac{E_{pk} I_{pk}}{R_p^{\,2}} \left(1 - \cos \theta_L \right). \qquad 8.$$

Collecting terms in equation 8 gives the theoretical dissipation of a class-B amplifier as a function of all possible variables as

$$P_d = \frac{E_{pk} I_{pk}}{R_p^{\,2}} \left(\frac{E_{cc} R_p}{E_{pk} F} - \cos \theta_L \right). \qquad 9.$$

For sinusoidal signals, where $R_p = 1.414$ and $F = 1.111$, equation 9 becomes

$$P_d = 0.5E_{pk}I_{pk} \left(1.274 \frac{E_{cc}}{E_{pk}} - \cos\theta_L \right), \qquad 10.$$

or

$$P_d = 0.5 \frac{E_{pk}^2}{Z_L} \left(1.274 \frac{E_{cc}}{E_{pk}} - \cos\theta_L \right) \qquad 11.$$

An expression for the theoretical efficiency of a class B amplifier may be obtained with the use of the definition

$$\eta = \frac{P_{out}}{P_{in}}. \qquad 12.$$

Substituting equations 2 and 3 in equation 12 gives

$$\eta = \frac{R_p F E_{pk} I_{pk} \cos\theta_L}{E_{cc} I_{pk} R_p^2}. \qquad 13.$$

Simplifying equation 13 gives the general expression for efficiency

$$\eta = \frac{E_{pk} F}{E_{cc} R_p} \cos\theta_L, \qquad 14.$$

which becomes, for sinusoidal signals

$$\eta = 0.785 \frac{E_{pk}}{E_{cc}} \cos\theta_L. \qquad 15.$$

It can be easily seen from either equation 6 or 10 that amplifiers using devices with pentode characteristics, where the peak voltage is nearly constant for changes in load impedance, have a dissipation which is directly proportional to the amplifier output-power or volt-amperes. This means that if dissipation for a particular amplifier-load characteristic becomes excessive, a reduction in output power by rematching will also reduce the dissipation.

Moreover, an examination of equation 11 reveals that dissipation is a function only of the peak voltage. Further, if equation 11 is divided by the power output to place dissipation on a per unit basis, the shape of this "dissipation" curve is seen to be constant for any power output, provided the peak voltage is the same. This is further

inferred from equations 14 and 15, in which efficiency is shown to be a function only of the peak voltage. This constant shape means that once an amplifier has been characterized as a function of impedance load for a particular matching and output power, rematching for a different output will, if the change is relatively small, cause only a change in the power scale of the dissipation and output power characteristics of the amplifier, and will not cause a change in their shape. (See Figure 2).

Likewise, the output voltage characteristic will remain constant both in shape and in value for small rematching. Output current, however, will change scale, but not shape.

Insofar as the actual shape of the dissipation-versus-peak-voltage characteristic is concerned, it can be inferred from equation 11 that, because power input increases linearly and power output increases on a square law, the maximum dissipation generally occurs not at the point of maximum output, but at some lower output. In fact, the point of maximum dissipation is at that point at which efficiency equals 50%.

Normal amplifier-design procedure, as is exemplified in the dissipation characteristic at Z_N in Figure 2, allows for this increase in dissipation by setting the dissipation at the 50% efficiency point equal to or less than the dissipation limit. However, if operation can be confined to either full output or to outputs which are less than approximately 25% of the full output, the increase in dissipation which occurs between these points is eliminated. The small dissipation which occurs at full output can then be set equal to the dissipation limit, allowing a much greater power output at the full output.

One further comment is in order concerning dissipation in pentode power-amplifiers. The theoretical-dissipation curve is increased by an amount equal to the quiescent current times the DC supply voltage for amplifiers which are operated in class AB or which have a large standby power. Likewise, the curves of dissipation versus impedance for various output levels are increased by the same factor, $E_{cc}\, I_q$.

POWER AMPLIFIER CHARACTERISTICS

The power amplifier which is being considered in this report is a class-AB push-pull system, manufactured by the Ling Electronics Division of Ling-Altec Corporation, Anaheim, California, and uses two RCA 6949 beam power tetrodes, giving a nominal output-rating of 1.3 Mw. The characteristics of this amplifier as a function of load impedance are enclosed as Figures 2 and 3. In these figures, constant input-signals are

used as a parameter for each curve. The input signals are adjusted at the nominal load-impedance to give outputs of 100%, 75%, 50%, and 10% of the rated value.

As is to be expected in an amplifier using pentode or tetrode vacuum-tubes, the output current as a function of load impedance is relatively constant; and both voltage and power decrease with reductions in load impedance. Further, as the output voltage decreases, the dissipation increases, becoming excessive when the reduction is such as to present a load impedance which is 0.88 of the nominal, matched value for an output of 1.3 Mw. The dissipation at output powers less than one-fourth the nominal output is either not excessive or is less than that at the nominal output. The normal peaking in dissipation at output powers between 0.25 and 1.0 P_{nom} is seen in Figure 2.

The characteristics contained in Figures 2 and 3 are based on the premise that the duty cycle is 10% or less and that the maximum on-time is one minute; the continuous-duty rating is 130 kw. Although the amplifier is designed for operation with loads having either leading or lagging power-factors between 0.9 and 1.0, operation at the 50%-efficiency point, approximately 800 kw, will require a load power-factor of better than 0.97 if excessive dissipation from reactive losses is to be avoided.

Since output power decreases at the same time as dissipation is increasing, the input power should remain relatively constant as a function of load impedance. Summation of these two characteristics as presented in Figure 2 shows that the input power increases by 1% as impedance is reduced from 1.05 Z_N to 0.82 Z_N, and increases only 6.1% with a further load reduction to 0.6 Z_N. Thus, the operating-efficiency characteristic for resistive loads has the same shape as the output-power curve for changes in load resistance.

Because the change in peak voltage-swing in the RCA 6949 tube is very small when changing output power, the output power versus matched-load resistance is a straight-line relationship for all general calculations.

TRANSDUCER CHARACTERISTICS

The transducer array which is presently being considered consists of 10 large magneto-restrictive ring units. Since they are magnetic, they have a constant-current transmitting-response; that is, the sound intensity in the water is nearly constant with a constant-current transducer drive. Although no data have been taken on the 400-cps rings to prove this, a study of the transmitting responses of a 10-kc model of the rings, Figures

3 and 4, indicates that the 400-cps rings should have a constant-current response. That this response is ideal may be seen by referring to the amplifier characteristic presented in Figure 3, in which it is seen that the amplifier output-current is relatively constant with changing impedance. Thus, all tuning networks should be in series with the transducer, keeping the transducer current constant, even though transducer power and voltage may vary widely.

There is considerable variation in the impedance of the transducer, and some uncertainty in the actual values of this impedance. At present, there is no data on the value of the impedance of the complete array nor the value of the impedance of a single element under hydrostatic pressure.

However, data on the impedance of a single element at the surface is available and this and the projected impedance value of the element in a completed array are presented in Figure 6 in the form of reactance-versus-resistance diagrams. The two circles labelled curve 1 and 2 are for equivalent circuits of the maximum and minimum-diameter circles which are expected.

It should be pointed out that past experience with transducers indicates that the impedance value of the actual array in the correct water-depth may and probably will be quite different from those given in the curves. Although the figures used herein are estimates for the specific transducer used in the ARTEMIS program, the range of impedance swing, the curve shape, and the techniques for correcting the impedance to a value which is relatively constant are generally true for all magnetic transducers.

It will be necessary to recompute the values of the tuning networks, etc., indicated herein when conclusive impedance data on the 400 cps rings become available; the estimates shown should be reasonably close. It is recognized that the impedance used is not correct; however, the major influence is on the transformer turns-ratio.

OTHER PERTINENT CHARACTERISTICS

The losses in the transmission line which connects the amplifier and transducer must also be considered. Further, in order to reduce the loss, it is necessary to use a high voltage line, thus requiring a matching transformer at the transducer. Five such transformers are used, each supplying two transducer elements from two secondary windings. The circuit which is used, and the estimated values of the parameters involved are shown in Figure 7.

Although there will be some loss in the output transformer of the amplifier itself, no attempt has been made to correct for this loss. The line and transducer-matching-transformer losses, however, have been included in the analysis. At the same time, the turns ratio of the matching transformer has been determined on the basis of present estimates of the transducer-element impedance.

OPTIMIZING OF SYSTEM DESIGN

Transducer Tuning

Because the transducer in this program has an electrical Q of approximately two, it is obvious that tuning will be required to prevent excessive amplifier dissipation. In order to take full advantage of the essentially-constant-current characteristic exhibited by both the transducer and the amplifier, series tuning is necessary.

Although transducers are generally tuned to resonate at the point of maximum resistance, estimated characteristics of the 400-cps transducer displayed two characteristics which indicated a desirability of tuning below the point of maximum resistance. The more obvious of these is the rather low transducer resonant frequency, whether this frequency is determined at the point of maximum resistance or at the diameter of the circle opposite the crossing points. Even though the required frequency of operation is not critical the mechanical vibration-characteristics of the array structure which has been designed for a 400-cps transducer might be affected by a large decrease in operating frequency, indicating that the frequency should be increased. The other reason for tuning below the maximum-resistance point appeared after a calculation of tuned impedance with resonance at the point of maximum resistance was made. This is that the impedance swing is reduced and equalized if the resonance point is lowered in frequency. This will be generally true in all magnetic transducers with very low Q, for the resistance of a low Q tuned circuit is not symmetrical, even though the reactance may be symmetrical.

The actual value of the tuned impedance as a function of frequency is given in Figures 8 and 9. The tuning capacitors were chosen to resonate the transducer at its point of maximum resistance in Figure 8 and below this point in Figure 9. The phase angle was held to less than 18.5° (PF = 0.95).

Initial System Operation

With the tuning fixed, the extreme variation in impedance made an initial analysis of amplifier operation desirable, even though many losses were neglected. Therefore Figure 10, which shows the output power or volt-amperes and the tube dissipation as a function of the relative impedance indicated on Figure 8 for curve 1 was calculated from the characteristic of Figure 2. The impedance indicated as 1.0 Z_N was assumed equal to the matched amplifier-impedance of 174 ohms.

It is immediately apparent that, for a matched output of 1.3 Mw, the very small impedance range permissible as shown in Figure 2 prevents successful operation over a 100-cps band. However, by rematching for an output of 1.0 Mw, as explained in the background, the power scale of Figures 2 and 10 will be changed, resulting in the second scales shown, permitting twice the impedance swing and an effective increase in the dissipation limit.

It would then seem to be within the realm of possibility that successful operation with a 100-cps noise-band held to an R_p of 1.414 can be achieved. Anticipating somewhat the details of utilizing less than four amplifiers, if the system is rematched for 3 amplifiers, 3-Mw output, and four amplifiers are used to supply the power, the power scale of Figure 10 can again be changed; resulting in the upper dissipation-limit-line and apparently successful operation over a 100-cps band with single-frequency sine-waves.

Line and Matching-Transformer Effects

The previous analysis has considered the transducer without including the transmission line and transformer loss and their effect on load impedance. The parameters to be considered are shown in Figure 7.

Before the line impedance can be included in the amplifier load, it is necessary to determine the reflected transducer-impedance at the matching-transformer primary. This, in turn, requires a determination of the transformer turns-ratio, which may be done in the following manner: Noting from Figure 7 that the line is represented by a symmetrical T, the receiving-end impedance which will give the proper amplifier load can be calculated by reversing the line and assuming that the sending-end impedance required by the amplifier is the receive impedance. The amplifier impedance corresponding to an output of 1.0 Mw is 226 ohms, and one-fourth of this (four amplifiers in parallel) is the proper line-sending-end impedance. The

calculation gives a sending-end impedance of 57.635 - j0.46 ohms. Re-reversing the line and adding the transformer parameters gives the reflected transducer-impedance required for the correct amplifier load as $58.25\underline{/0.9^\circ}$ ohms.

Since 10 transducers are used, the reflected impedance of one element must be 582.5 ohms. Figure 9 shows that the impedance of curve 2 at 360 cps is 1.81 ohms. This gives an impedance ratio for the matching transformer of 322 : 1, or a voltage ratio of 17.9 : 1.

Using this matching-transformer turns-ratio, it is now possible to calculate the amplifier load over the frequency band in question. Considering curve 2, Figure 9, the resulting impedance characteristic is given in Figure 11 and the output and dissipation of the amplifier with this load is given in Figure 12. It should be noted that the transducer was tuned below the maximum-resistance point for this determination.

By retuning the transducer to a point near the maximum resistance, the dissipation at the high end of the frequency band was reduced slightly. At the same time, the turns ratio was dropped to 310:1 to increase the output power. The resulting impedance characteristic is shown in Figure 13 and the amplifier output and dissipation in Figure 14.

The load impedance, and output and dissipation for curve 1 tuned below the maximum-resistance point, are given in Figures 15 and 16, respectively.

Although these results provide better operating characteristics than the preliminary calculations indicated, there is still a tendency for excessive dissipation to occur, especially when using single-frequency sinusoidal-signals. Successful operation under these conditions can be attained; however, excessive dissipation may cause amplifier shut-down, by means of the over-temperature protection, in less than the normally permissible one-minute on-time.

Impedance-Smoothing Network

Inasmuch as it was felt that the performance cited in the foregoing section should be improved upon, some type of network was required which could smooth out the impedance swing without increasing the value at the point where line impedance was already a maximum.

Such a network is the series-parallel-resonant network shown in Figure 17 and inserted aboard ship between the matching

auto-transformer and the transmission line. The drop in resistance component which occurs in the line impedance at the point of high-frequency reactance-peaking (approximately 410 cps) can be cancelled by adding in series the multiplied resistance which is available in a parallel-resonant circuit. The increased impedance which would otherwise occur at 360 cps is partially cancelled by series resonating the residual inductance of the parallel circuit. This also reduces the added reactance of the parallel network between 360 and 410 cps. Because the network is in series with the transducer, the transducer current is still relatively constant, and a constant sound-output level should be generated. even though as much as one-half the amplifier output-power is dissipated in the coil of the parallel-resonant circuit at high frequencies.

Two sets of network parameters were investigated, and, although the second set is more attractive, the results of both are included. Using a circuit Q of 10, and tuning for parallel resonance at 420 cps, resulted in a coil of 0.946 mh., a coil resistance of 0.249 ohms, a parallel capacitance of 151 mf., and a series capacitance of 75.1 mf. The effective resistance of this network (Number 1) was, at parallel resonance, 25.1 ohms, the correct value for curve 1, Figure 15. The amplifier impedance for curves 1 and 2, Figures 15 and 13 respectively, with this network in series with the line is given in Figure 18, and the resulting power output and dissipation in Figure 19.

Because the upper-frequency limit of operation was still considered inadequate, but more important, because the dissipation at the upper-frequency limit tended to increase rather rapidly, a new set of network parameters (Number 2) was used. The parallel-resonant frequency was increased to 440 cps, and the Q was reduced to 5 in order to keep the network reactance peak at the same frequency. This resulted in a coil of 1.98 mh., a coil resistance of 1.108 ohms, a parallel capacitance of 66.2 mf., and a series capacitance of 51.59 mf. The effective resistance of this network increased to 27 ohms. The impedance load of the amplifier which resulted is given in Figure 20, and the calculated amplifier-output-power and dissipation in Figure 21.

The amplifier characteristics which are a result of this second network are very encouraging. To begin with, the frequency band over which any type of operation is permissible is much wider than the required 100 cps. Also, the dissipation tends to increase rather slowly at both ends of the band. However, most important is the fact that the dissipation and the output power for either of two rather different transducer-impedance characteristics are almost identical in character, indicating that the uncertainty in transducer impedance may not be troublesome.

Because output power as shown in Figure 19 and 21 was a little smaller than was considered desirable, a new calculation of the line sending-end impedance was made using an impedance ratio of the matching transformer of 279:1, 10% less than before, with curve 1, Figure 13, for the transducer impedance. The resultant impedance and the output power and dissipation for this impedance for both networks are given in Figures 22 and 23, respectively. Under this condition, the advantage of the second network becomes obvious. Similar results can be expected if the same process is carried out for curve 2.

Because the dissipation of the coil resistance in the series-parallel network is very high, 1.6 Mw to 2.4 Mw, depending on the output power and the network parameters, it is felt that the coil should be more than one unit, thus spreading the heating over several coils.

System-operating plans, which are detailed later, also lead to the desirability of more than one coil. Moreover, the necessity of using transducers in pairs as they are supplied and in the event of a casualty, makes separate networks definitely a requirement. This, fortunately, reduces the size of the capacitors, for with 5 networks, there are 5 pairs of transducers, the impedances of each individual component must be increased by a factor of 5, thus reducing the capacitors to 13.24 mf., and 10.32 mf., for network Number 2. The inductance is increased to 9.9 mh and the coil resistance to 5.54 ohms.

Because both transducer impedance and network impedance obey the same laws as the number of units is altered, the shape of the system impedance curve will be identical in all cases, provided the element impedance of the transducers remains constant.

Since this, of course, is not the case, because of the change in array loading with reductions in the number of elements, the above statement is not quite true; however, it is felt that the effect of the network on the line sending-impedance will allow much more constant amplifier load than would be the case if the reflected transducer-impedance by itself were used. Besides, as will be shown later, the use of less than the full number of transducers allows considerable leeway in the choice of the number of amplifiers which are to supply the now reduced output-power. Then, too, the change in transducer element impedance when using less than a full array is likely to be an increase from the value obtained in a full array. This will reduce both power output and dissipation from the value which would be expected when

considering element impedance in a full array, and will counterbalance the reduced effectiveness of the smoothing network.

COMPLETE SYSTEM OPERATION

The necessity of repairing, maintaining, and testing the equipment, as well as the requirement for continuous operation at all times, make it desirable that any number of amplifiers from one to four, or any number of pairs of transducers from one to five be usable in any combination. These two devices, amplifiers and transducers, may be considered separately.

The necessary rematching for using other than four amplifiers on the line is provided by a step-down autotransformer between the amplifier-output transformers and the line. When all four amplifiers are being used, the autotransformer is not in the circuit. As the number of amplifiers is decreased, the load impedance must be increased to prevent excessive power output. This is accomplished by means of the autotransformer. For three amplifiers, the impedance of the line is increased by 1.33; for two amplifiers, by 2.0; and for one amplifier, by 4.0, neglecting autotransformer losses.

When the number of transducers on the line is considered, however, the line-sending-end impedance itself is altered. As the number of pairs is reduced the impedance is increased. On a relative basis, this increase is 1,1.25,1.67,2.5, and 5 for numbers of pairs from five down to one. Therefore, with five pair of transducers on the line and the four amplifiers producing rated power, the amplifier output power as the line sending-impedance changes due to a reduction in the number of pairs or elements is reduced by the proper amount for correct transducer operation. For this reason, the autotransformer may remain at the same ratio during all the transducer changes as that determined by the number of amplifiers used for the full complement of transducers.

Having disposed of the necessary amplifier and transducer changes, one can now consider one more important factor before establishing the operating characteristics of the complete system. As has been indicated in the background of this report, the power amplifiers being considered display the usual increase in dissipation as power is reduced from the maximum unclipped value. In fact, the dissipation, assuming load impedance is constant, is greater than that at the maximum output for all powers between 60% and 100% of the maximum output at best, and may be greater even at outputs as low as 20%, although not excessive in this case.

For this reason, and because efficiency also remains much greater if full output is maintained, it is best to operate each power amplifier only at full output or at those outputs less than 20% of this full value. That this is not really detrimental to good operation will soon be apparent.

It is obvious, of course, that, when operating the system at reduced power, it is unnecessary and undesirable to use all of the available amplifiers. Since this is so, it is possible to control the output power by rematching and removing amplifiers, while at the same time allowing full output from each amplifier. The nominal-output powers which are obtainable in this way, as well as the necessary autotransformer taps and the power reduction in decibels from the maximum are given in Table II. In addition, the corresponding values are also given in Table II for combinations of transducer elements less than the normal number. The DC input power requirement for these same conditions is given in Table III.

To allow for reductions in level with a full array to less than 1 Mw, the amplifiers must be operated at the low efficiency 20% power point. Applicable values are given in the tables.

Finally, if transducer loading for some particular condition is such as to cause excessive dissipation, operation will still be possible at all but the maximum-output power by adding one more amplifier than is indicated in Table II to provide the power, thus further dividing the dissipation among the amplifiers.

CONCLUSIONS AND RECOMMENDATIONS

In order to summarize and condense the results, the following conclusions and recommendations are made:

1. Operation of the ARTEMIS power-amplifiers at an output of 4 Mw with either single-frequency sinusoidal or noise signals which are band-limited to a 100-cps band and are clipped to a peak-to-rms ratio of 1.414 is achievable, under the condition that a network is used to reduce the transducer-impedance variation.

2. The frequency band of operation can be the originally postulated 350 to 450 cps, again under the condition that the impedance-smoothing network is used.

3. The impedance-smoothing network that should be used is one which is parallel resonant at the upper end of

the frequency band and is series resonant at 360 cps. It should be mounted at the amplifier between the autotransformer and the line, and should consist of five identical networks. The number of networks which are in parallel at any time should be equal to the number of pairs of transducer elements which are being used. The recommended values for the network parameters are: Coil inductance, 9.90 mh; coil resistance, 5.54 ohms; parallel capacitance, 13.24 mf; and series capacitance, 10.32 mf, and are relatively independent of the magnitude of the transducer impedance, but depend upon the shape of the circle (X/R ratio). There will be approximately 400 to 500 kw of heat to be dissipated in each coil when operating at 440 cps.

4. The average tuning-capacitance is 150 μf, but may change by $\pm$ 10 μf with different transducer-impedance circles. The average valve should be adequate if the impedance-smoothing network is used.

5. It may be possible to operate the system without the use of the smoothing network. However, when single-frequency signals are used, the operation will be marginal, and the bandwidth will have to be reduced and lowered, and the pulse length may have to be shortened. Transducer-load impedance will have great effect on the necessary reduction in performance. It is recommended, therefore that, in any case, but especially for this type of operation, the actual line sending-impedance be determined with the correct transducer operating environment at gradually increasing powers, using a sufficient number of the power amplifiers to prevent excessive dissipation under any possible loading condition.

6. If difficulty is experienced with amplifier shutdown because of excessive dissipation, full pulse-length may be achieved, and shutdowns avoided, by rematching the amplifiers with the autotransformer for the next lower power which sacrifices only 1.25 db of output.

7. Each amplifier should be operated at full-power output for the matching being used, giving the system operating characteristics detailed in Tables II and III. If other than full output is used, it is recommended that no more than 20% of the full output be used, even though more than this can often be obtained safely.

8. Operation with less than the full complement of transducer elements is achievable. If the shipboard smoothing-network is used, there should be no difficulty with excessive dissipation. However, if some difficulty is experienced, or

when operating without the network, the addition of one more amplifier than indicated in Tables II and III will solve the problem.

9. The matching transformer at the transducer end of the line should have an impedance ratio based on estimates contained herein of 310 : 1, and should be tapped to provide ±10% and ± 20% of this ratio. The system characteristics shown in Table II will have a variation of perhaps ±0.5 db in power because of the transducer-impedance variation.

10. The DC-power-supply load is tabulated in Table III. Once the transducer-load matching has been set, this load is nearly constant (see Figure 24) for any one power condition for all signals; the variation is no greater than ± 25 kw. Variation with the transducer load will be quite high for the same power matching, as much as ± 150 kw for each amplifier.

11. It is emphasized that the band of operating frequencies must be limited to 100 cps, with very sharp fall off on both sides of the band, particularly if operation without the impedance-smoothing network is contemplated. Also, the peak-to-rms ratio of any signals used must be less than 1.414.

12. Although the specific values developed herein are for use with the ARTEMIS Program and its components, the analysis and techniques which are used are applicable to all systems using a magnetic transducer.

Table 1.
Relative Power-Levels of Class-B Amplifiers with Theoretical Active-Devices

Type of Amplifier	Output	Input	Diss.	Efficiency	R_{L1}/R_{L2}	λ_1/λ_2	P_{d1}/P_{d2}
Triode at Z;Fig. 1a	9	24	15	0.375	2	1.5	1/1.6
At reduced Z	8	32	24	0.250			
Triode at Z;Fig. 1b	27	40	13	0.675	2.25	1.125	1/2.46
At reduced Z	48	80	32	0.600			
Pentode at Z; Fig. 1c	7	10.67	3.67	0.656	1.75	1.75	1/1.82
Pen. at Reduced Z	4	10.67	6.67	0.375			
As cath. follower	9.76	17.1	7.34	0.570			

Table II
Operating Characteristics for the ARTEMIS-Power-Amplifier System
Output-Characteristics

Number of T/D Elements On Line	Output Power in Kilowatts	Percent of Max. Output of 4.0 Mw.	DB Down from Maximum Level	Number of amplifiers On Line	Transformer Tap in Terms of Amplifier No.
2	0-160	0-4	14	1	4
2	400	10	10	1	2
2	800	20	7	1	4
4	0-320	0-8	11	2	4
4	800	20	7	1	2
4	1600	40	4	2	4
6	0-480	0-12	9.2	3	4
6	1200	30	5.2	2	2
6	2400	60	2.2	3	4
8	0-640	0-16	8	3-4	4
8	1600	40	4	2	2
8	3200	80	1	4	4
10	0-200	0.5	13	1	1
10	500	12.5	9	2	1
10	1000	25	6	1	1
10	2000	50	3	2	2
10	3000	75	1.25	3	3
10	4000	100	0	4	4

Table III
Operating Characteristics for the Power-Amplifier System
DC-Input Characteristics

No. of T/D Elements On Line	No. of Amplifiers On Line	Amplifier Output Power In Kilowatts	No. Signal DC Input Power in kw	DC Input Power With Applied Signal KW
2	1	0-160	200	200-520
2	1	400	200	580
2	1	800	200	1160
4	2	0-320	400	400-1040
4	1	800	200	1160
4	2	1600	400	2320
6	3	0-480	600	600-1560
6	2	1200	400	1740
6	3	2400	600	3480
8	3-4	0-640	600-800	600/800-2080
8	2	1600	400	2320
8	4	3200	800	4640
10	1	0-200	200	200-650
10	2	500	400	1000
10	1	1000	200	1450
10	2	2000	400	2900
10	3	3000	600	4350
10	4	4000	800	5800

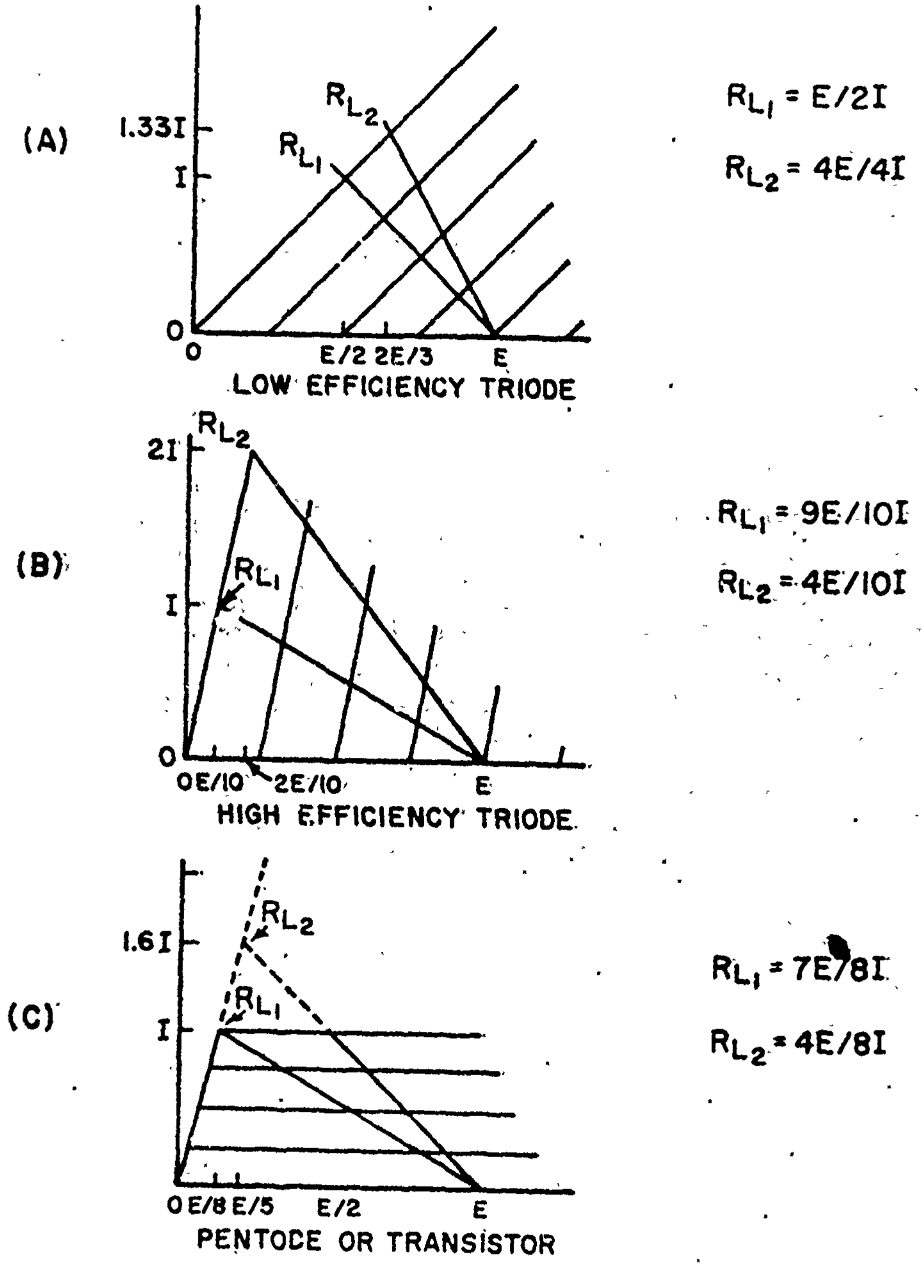

Fig. 1 - Idealized Output Characteristics of Triodes and Pentodes

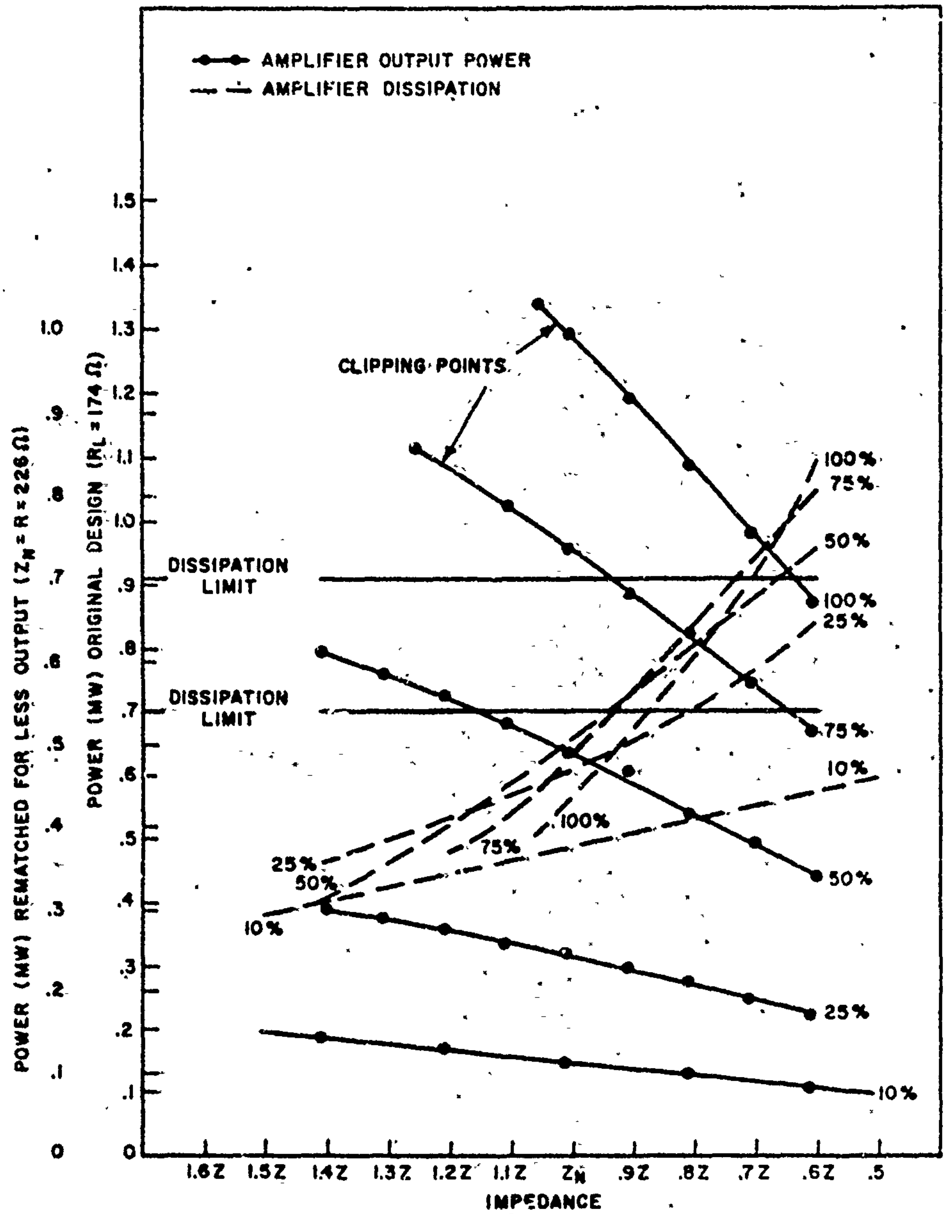

Fig. 2 - Project Artemis - Output Power and Dissipation for One Ling Power Amplifier (Constant Amplifier Drive for Stated Percentage Power Output is Assumed)

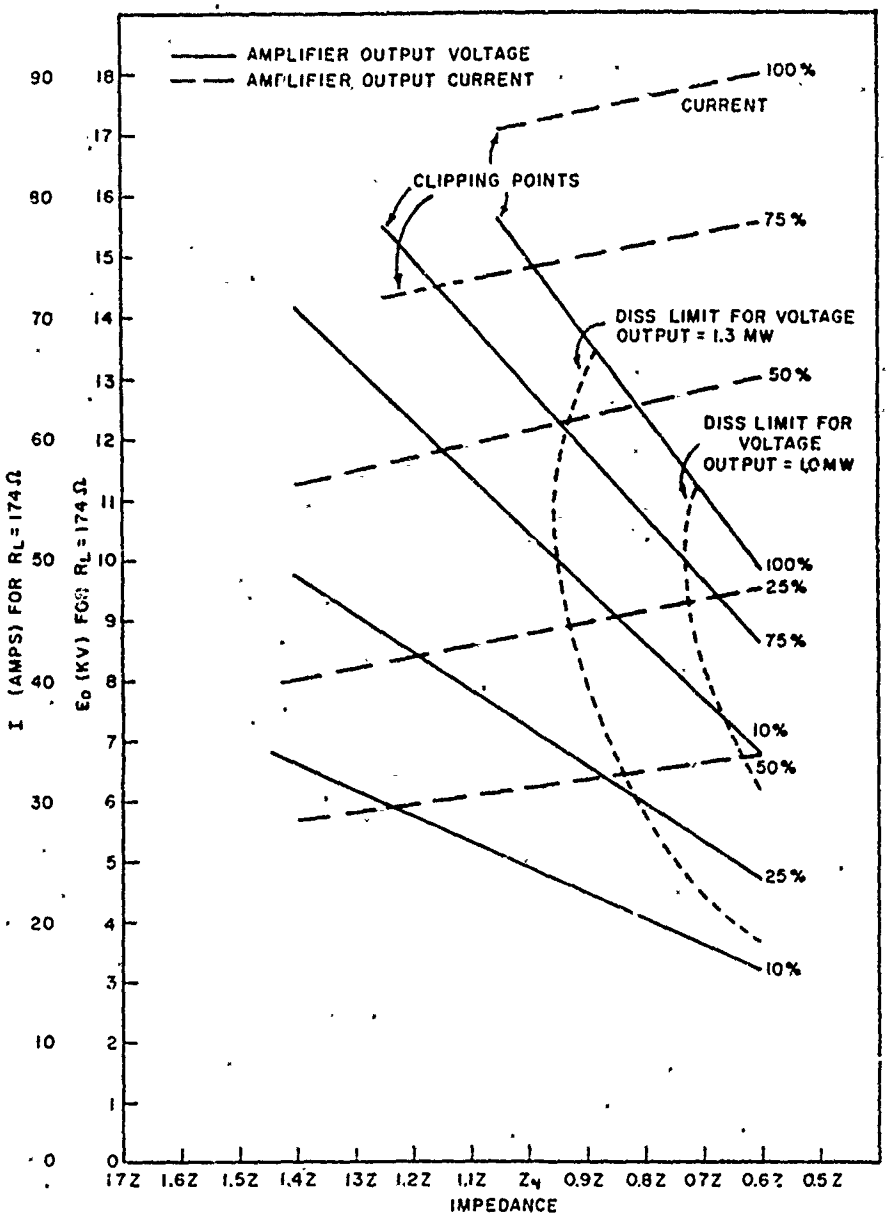

Fig. 3 - Project Artemis - Output Voltage and Current for One Ling Power Amplifier (Constant Amplifier Drive for Stated Percentage Power Output is Assumed)

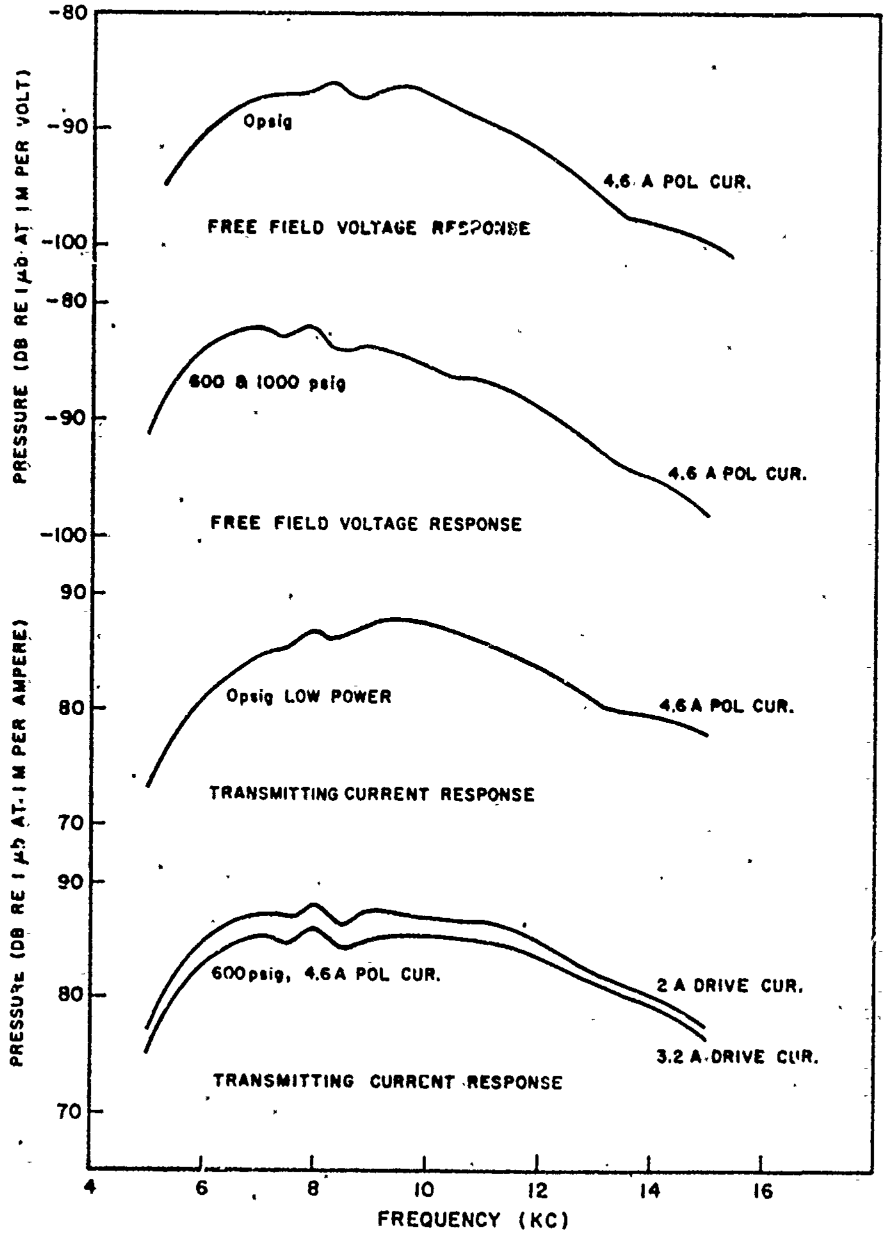

Fig. 4 - Transmitting Responses, Element #3, DT-80, 10 kc Transducer Model

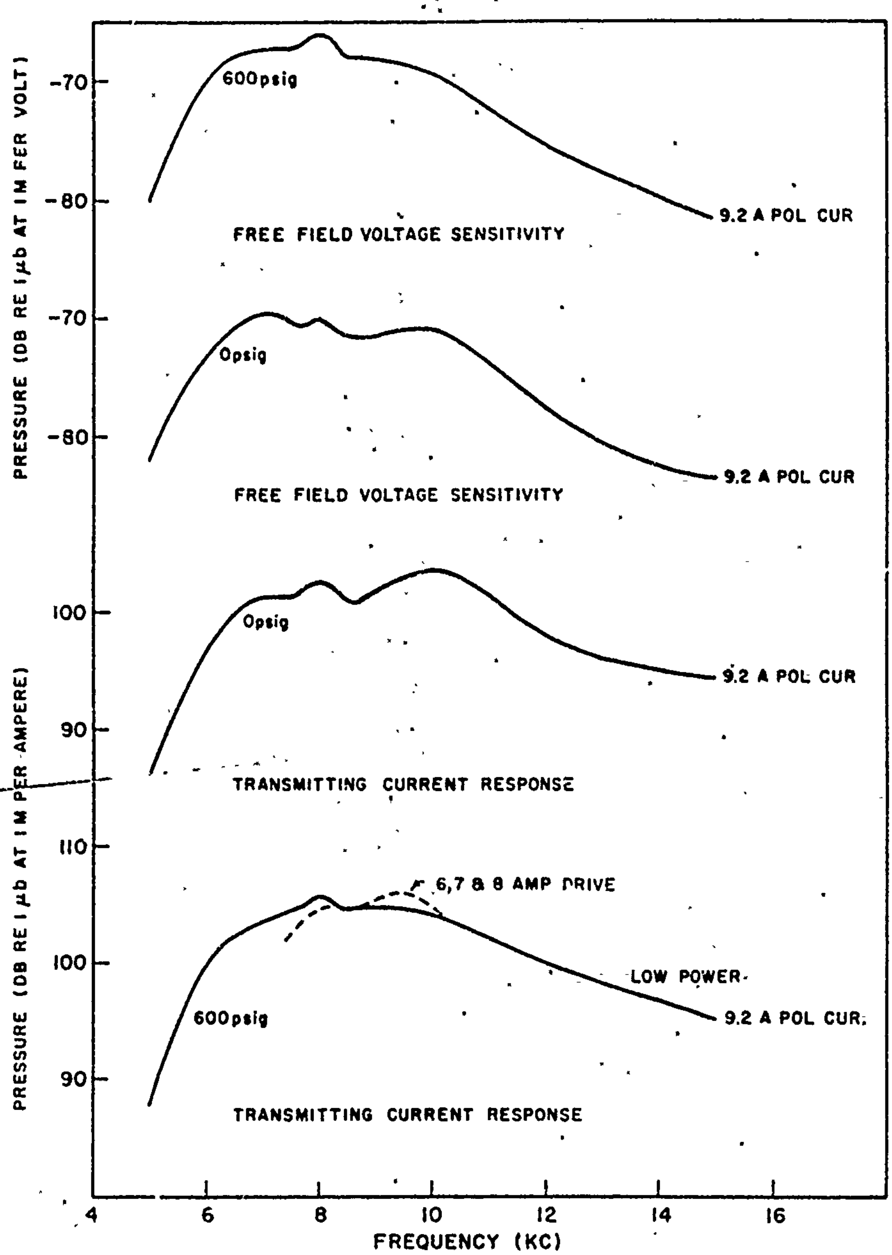

Fig. 5 - Transmitting Responses, DT-80 Elements, 10 kc Array of 10

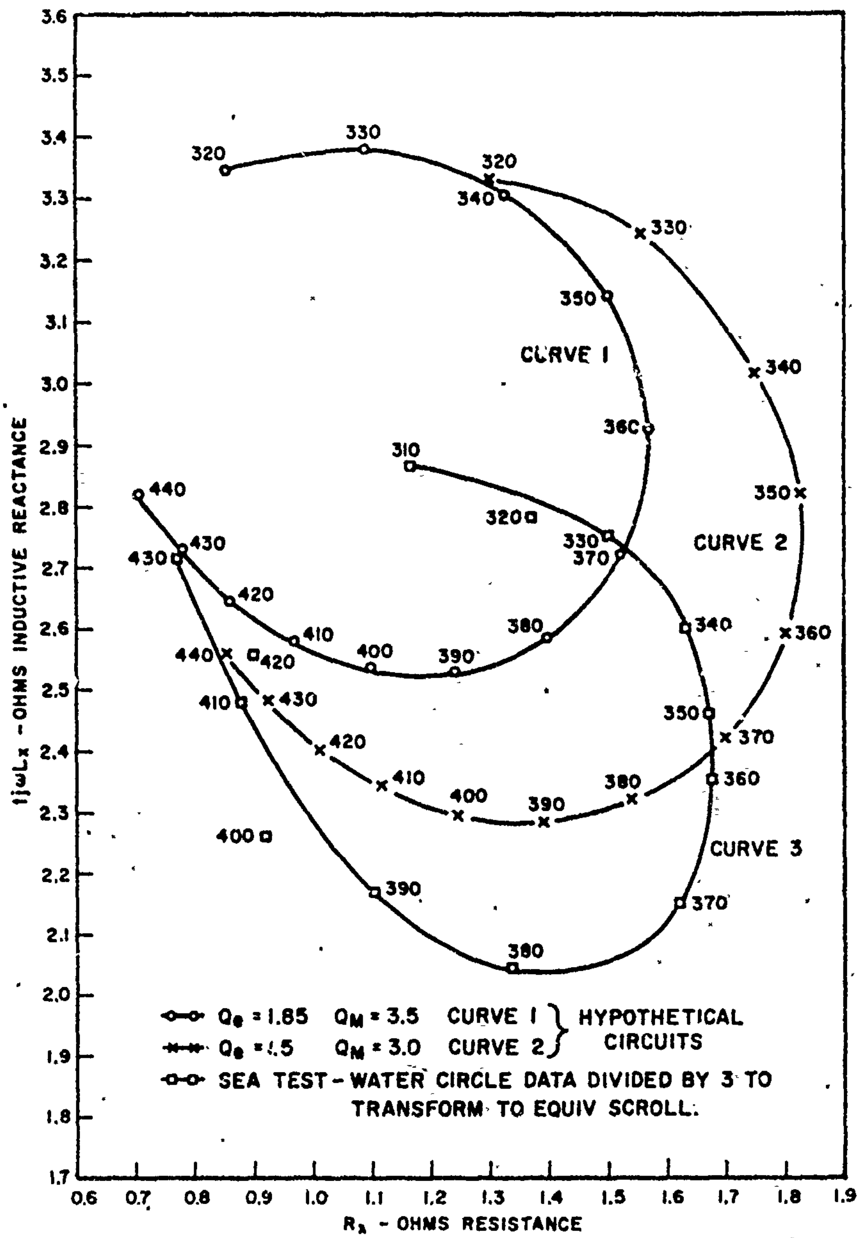

Fig. 6 - Artemis Scroll Impedance Diagrams

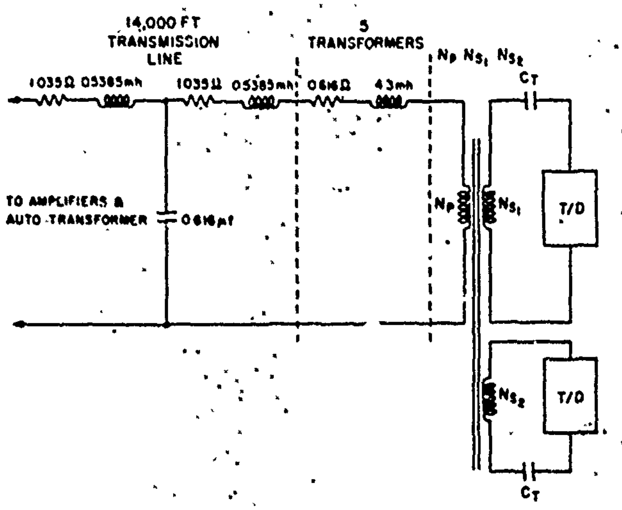

Fig. 7 - Line and Transducer Matching Transformer Parameters

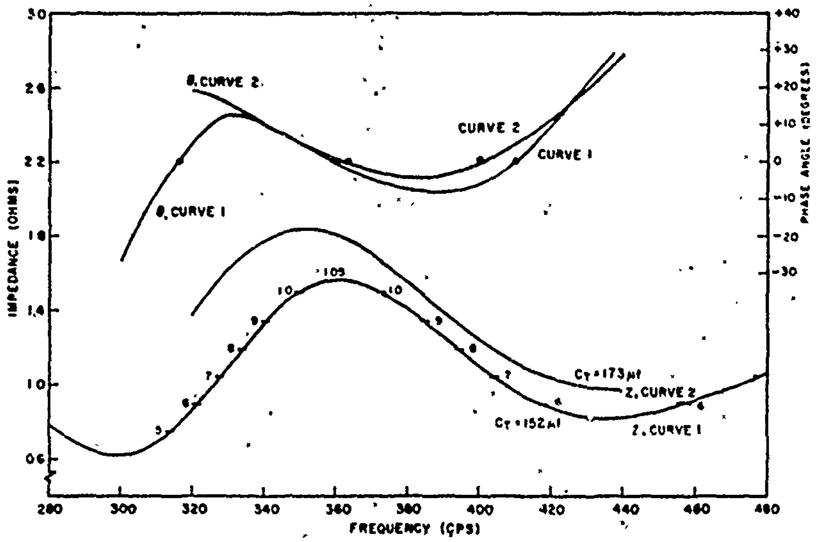

Fig. 8 - Transducer Tuned Impedance Tuned at Point of Maximum Resistance

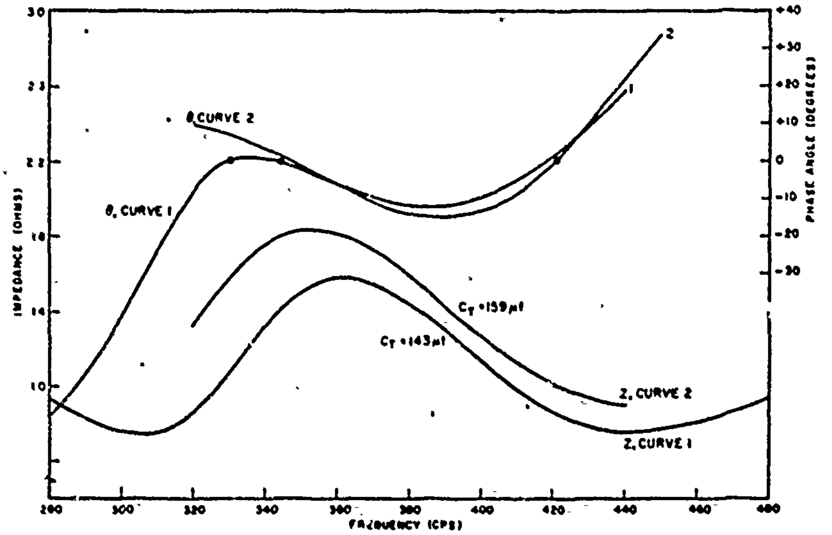

Fig. 9 - Transducer Tuned Impedance Tuned at Point Below Maximum Resistance

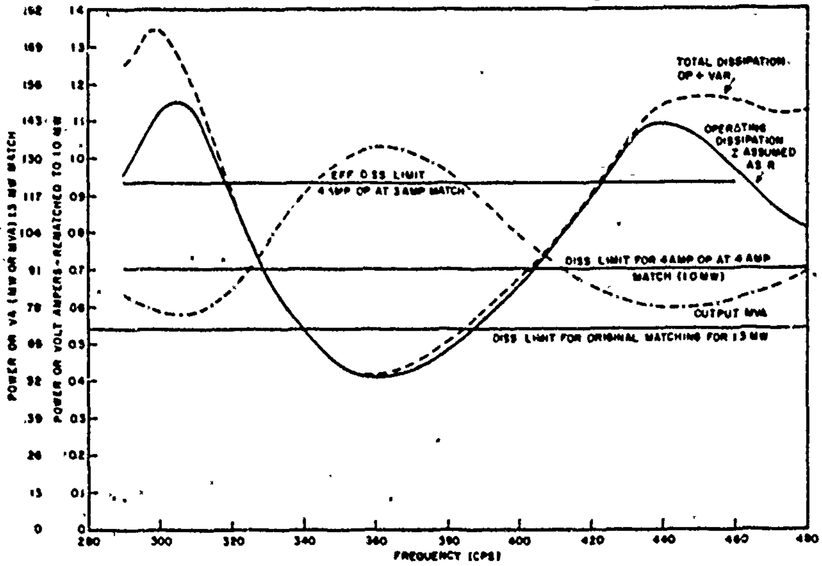

Fig. 10 - Ling Amplifier Operation, Simple Series Tuning, Eq. Circuit of Curve 1

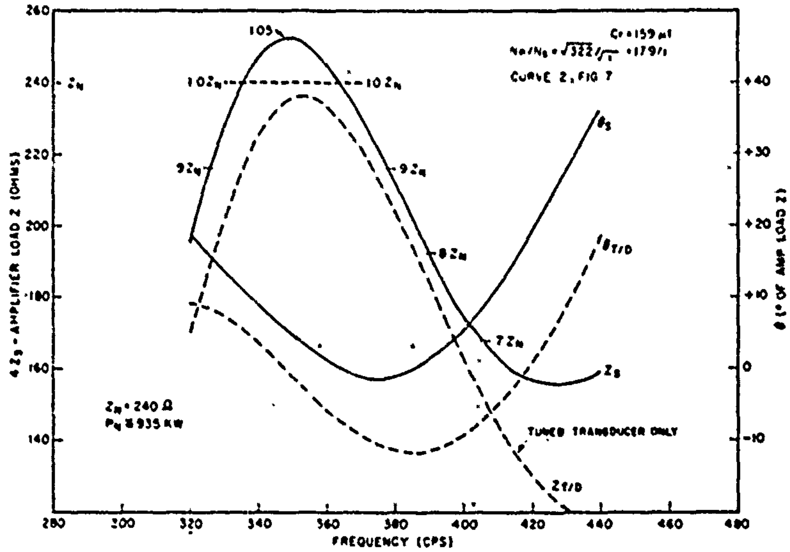

Fig. 11 - Amplifier Load Impedance Characteristic

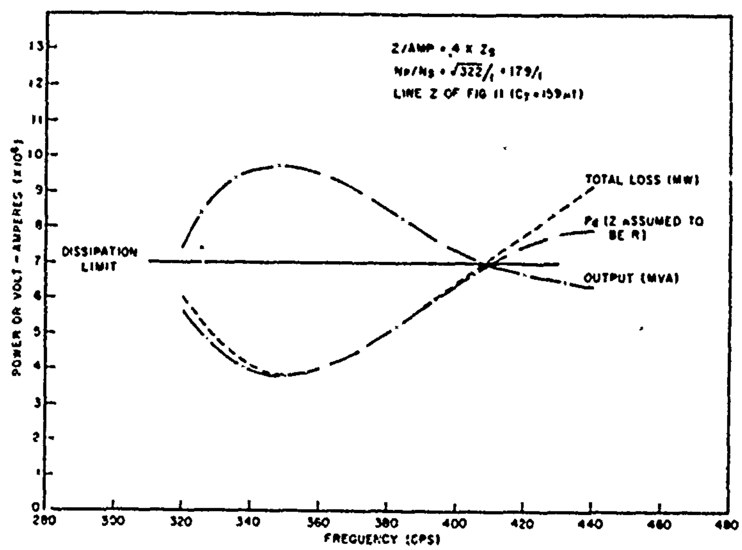

Fig. 12 - Amplifier Output and Loss vs Frequency

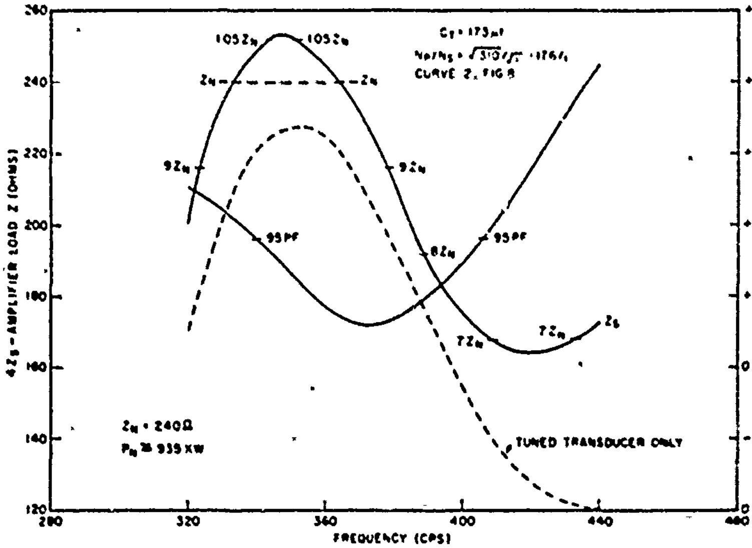

Fig. 13 - Amplifier Load Impedance Characteristic

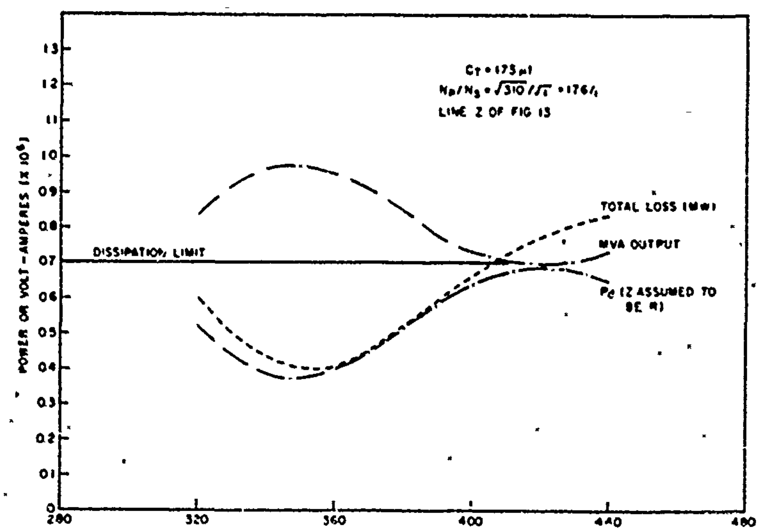

Fig. 14 - Amplifier Output and Loss
vs Frequency

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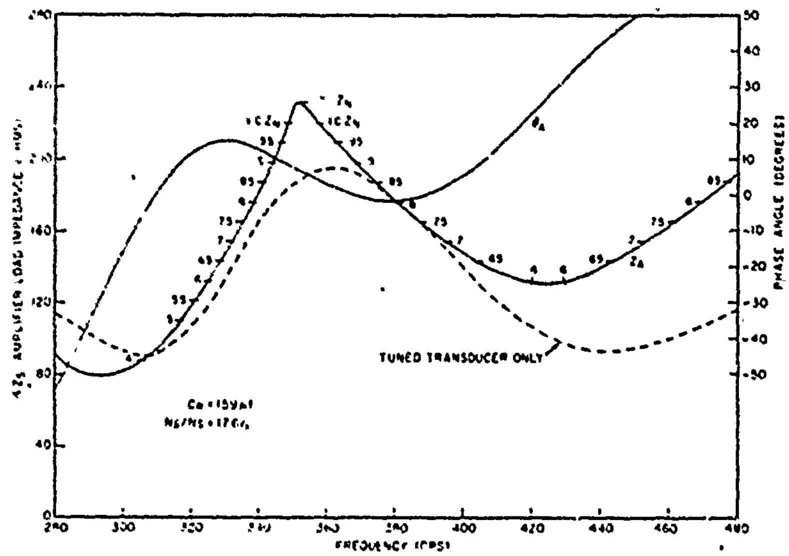

Fig. 15 - Amplifier Impedance Characteristic for Curve 1, Fig. 9

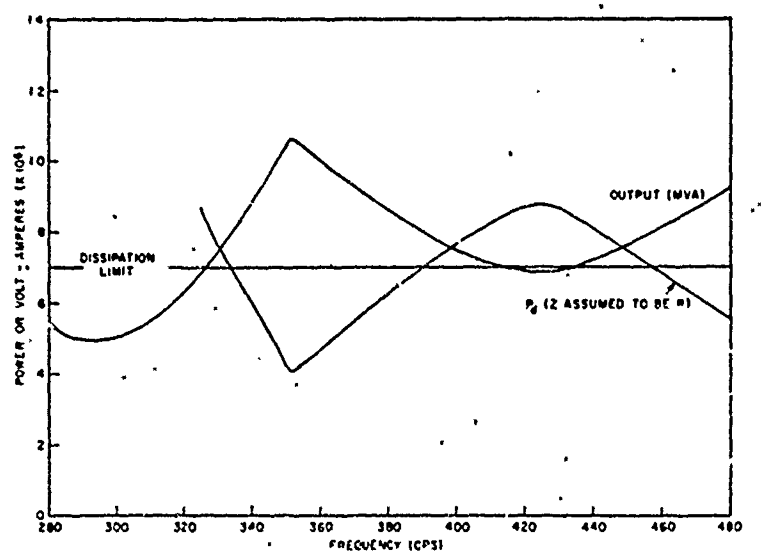

Fig. 16 - Amplifier Operating Characteristic for Curve 1

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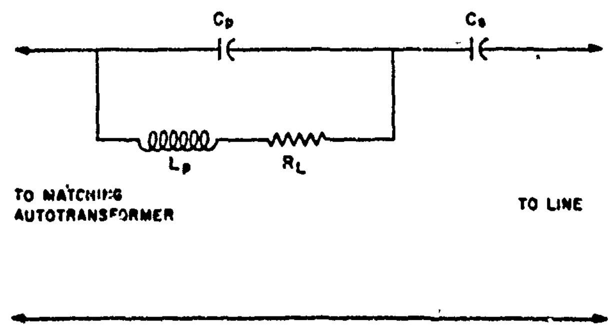

Fig. 17 - Impedance Smoothing Network

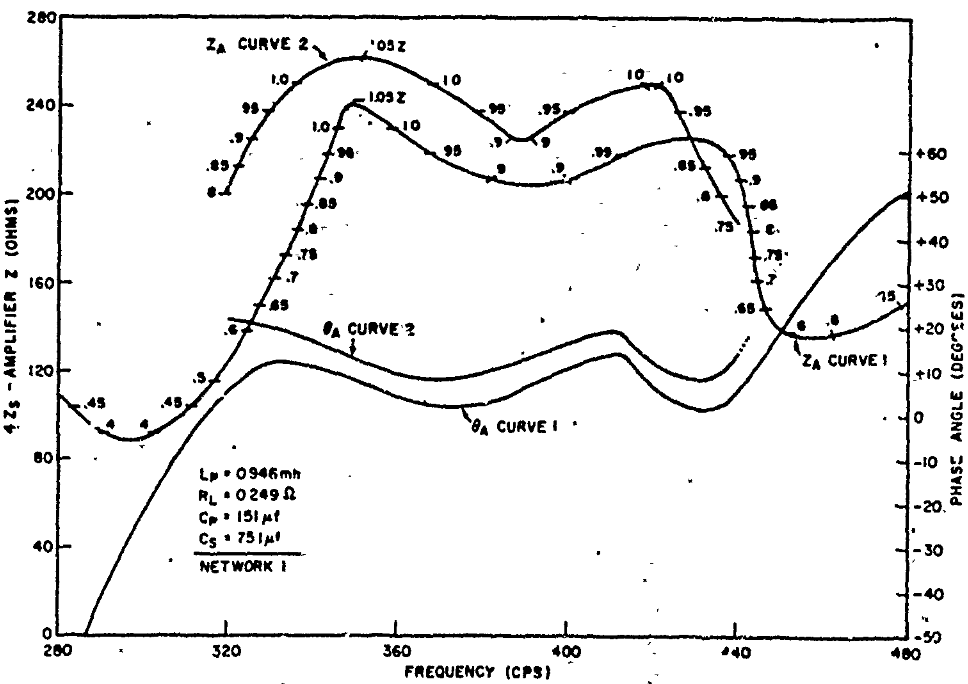

Fig. 18 - Impedance Diagram for Transducer Curves 1 and 2, Line Match of 310:1

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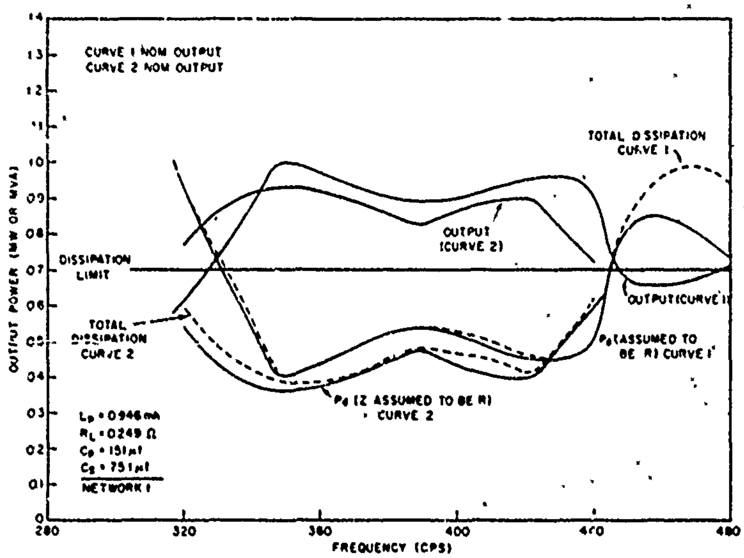

Fig. 19 - Amplifier Operating Characteristics at 310:1, Curves 1 and 2

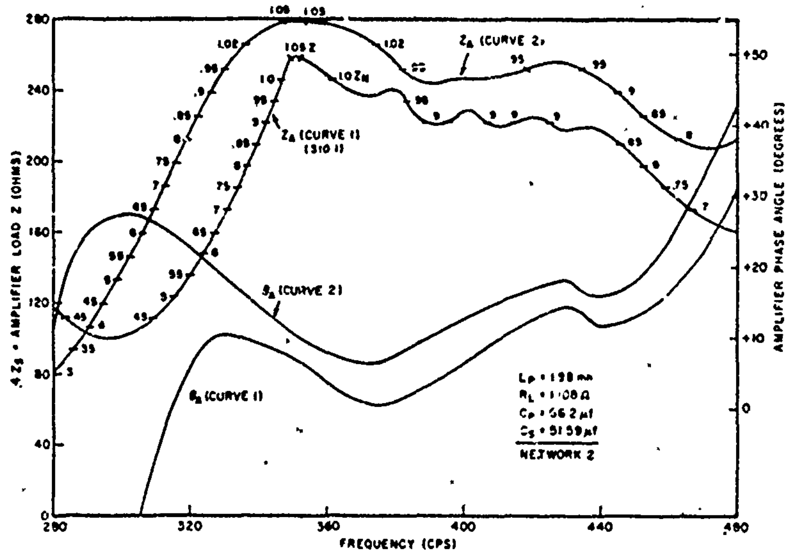

Fig. 20 - Amplifier Impedance Curves 1 and 2 at 310:1

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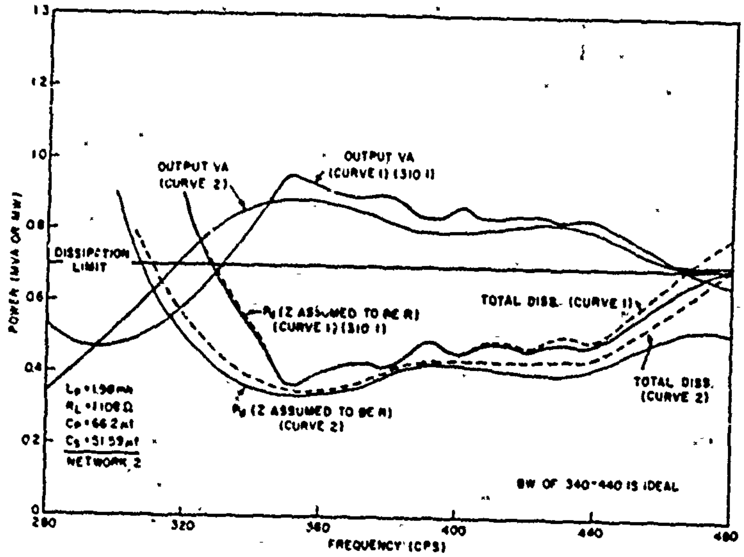

Fig. 21 - Amplifier Operating Characteristics Curves 1 and 2 at 310:1

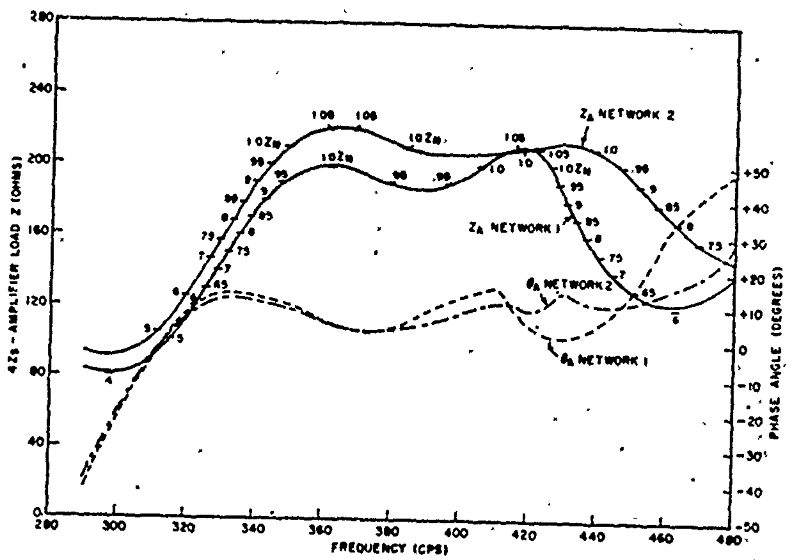

Fig. 22 - Impedance Diagram for Transducer Curve 1, Lire Match of 279:1, Networks 1 and 2

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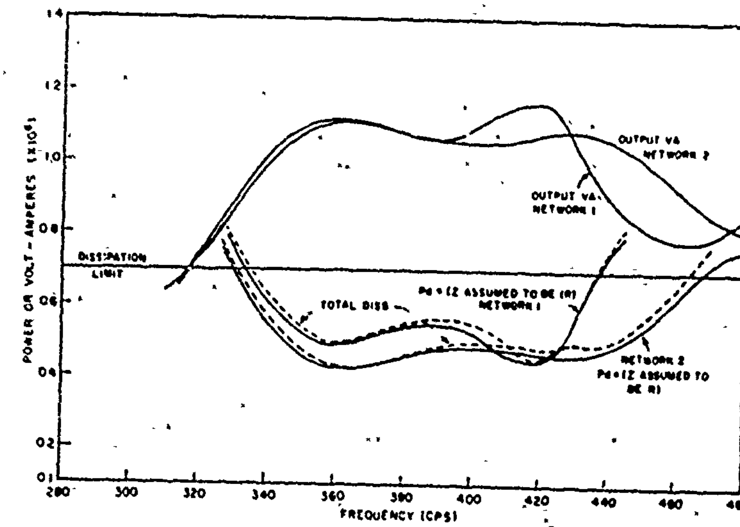

Fig. 23 - Amplifier Output Characteristics for Curve 1 at 279:1

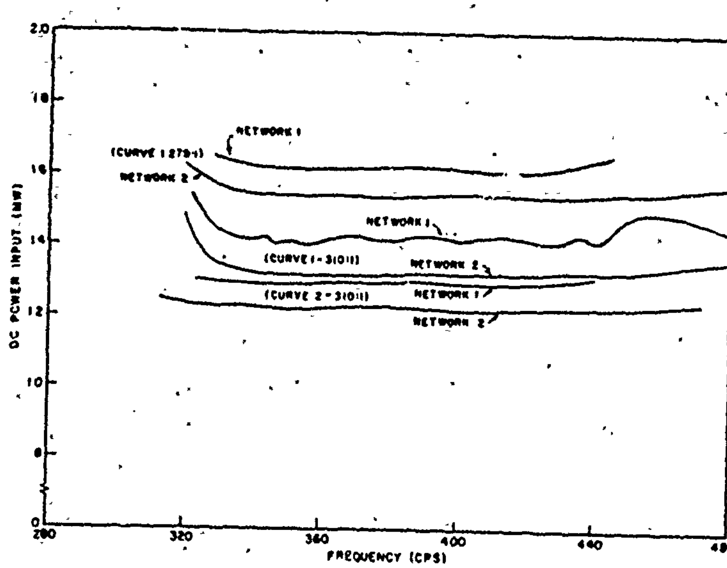

Fig. 24 - Amplifier D.C. Input Power for Various Load Conditions

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